

Magnetic braking of Ap/Bp stars: an alternative formation mechanism of compact intermediate-mass binary pulsars

Wei-Min Liu¹, Wen-Cong Chen^{1,2*}

¹ *School of Physics, Shangqiu Normal University, Shangqiu 476000, China;*

² *Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, China*

ABSTRACT

It is difficult for the intermediate-mass X-ray binaries (IMXBs) evolutionary channel to form intermediate-mass binary pulsars (IMBPs) with a short orbital period (less than 3 d) via stable mass transfer. The main reason is that the magnetic braking mechanisms are generally thought not to work for donor stars with a mass of greater than $1.5 M_{\odot}$ in the canonical model. However, some intermediate-mass stars have anomalously strong magnetic fields (about 100 – 10000 G), i. e. so-called Ap or Bp stars. With the coupling between the magnetic field and the irradiation-driven wind from the surface of Ap/Bp stars, a plausible magnetic braking mechanism should be expected. In this work, we attempt to investigate if IMXBs with Ap/Bp stars can produce IMBPs with a short orbital period (less than 3 d) by such an anomalous magnetic braking mechanism. Using a stellar evolution code, we have simulated the evolution of a large number of IMXBs consisting of a NS and an Ap/Bp star. For the spin evolution of the NS, we consider the accretion torque, the propeller torque, and the spin-down torque caused by the interaction between the magnetic field and the accretion disc. The calculated results show that, employing anomalous magnetic braking of Ap/Bp stars, IMXBs can evolve into compact IMBPs with short orbital periods of less than 3 d. However, there exists significant discrepancy between the spin periods of IMBPs in our simulated results and those observed.

Key words: binaries: general – stars: neutron – stars: peculiar – stars: magnetic field – stars: evolution

1 INTRODUCTION

Binary millisecond pulsars (BMSPs) consist of a millisecond radio pulsar and a white dwarf (WD). Their observed orbital and stellar parameters are fossils of binary stars evolution. Thus BMSPs can be used as important probes to test stellar astrophysics and binary evolutionary theory. According to the nature of the WD companions, BMSPs were divided into two groups: low-mass binary pulsars (LMBPs) and intermediate-mass binary pulsars (IMBPs). Nowadays, it is generally accepted that most LMBPs are evolved from neutron star (NS) low-mass X-ray binaries (LMXBs). By Roche-lobe overflow of the progenitor of the WD, NS can be spun up to a millisecond period via the accretion of material and angular momentum from the donor star (Alpar et al. 1982; Radhakrishnan & Srinivasan 1982). At the same time, the mass accretion induces the NS magnetic fields decrease to about $10^8 - 10^9$ G (Konar & Bhattacharya 1997). The final evolutionary endpoints are LMBPs consisting of a millisecond pulsar and a low-mass (less than $0.4 M_{\odot}$) He WD

(see Bhattacharya & van den Heuvel 1991; Tauris & Savonije 1999; Podsiadlowski et al. 2002; Tauris & van den Heuvel 2006).

Comparing with LMBPs, IMBPs consist of a massive (greater than $0.4 M_{\odot}$) CO or ONeMg WD and a mildly recycled pulsar (Camilo et al. 1996, 2001; Edwards & Bailes 2001a), in which the spin periods and magnetic field strengths are considerably greater than those of LMBPs (Li 2002). Furthermore, IMBPs tend to have a relatively short orbital-period (less than 40 d) and a relatively large orbital eccentricity. These properties imply that there exist different progenitor systems and evolutionary histories between IMBPs and LMBPs. The CO WDs can evolve from normal intermediate-mass hydrogen-rich stars on asymptotic giant branch by burning hydrogen and helium shells around the CO core (van den Heuvel 1994). Therefore, it is generally agreed that IMXBs can evolve into IMBPs. Due to the large mass ratio (more than 1.5) of IMXBs, the mass transfer was thought to be unstable, and lead to a common envelope evolution (Paczynski 1976; Webbink 1984; Iben & Livio 1993). With the spiral-in of the NS in the envelope of the donor star, it will be mildly recycled by a short timescale super-

* E-mail: chenwc@pku.edu.cn

Eddington accretion (van den Heuvel & Taam 1984; Stairs 2004). However, a NS may collapse into a black hole during hypercritical accretion in the common envelope phase (Chevalier 1993; Brown 1995; Brown et al. 2001). Subsequently, it was discovered that, except for the donor stars with a deeply convective envelope, IMXBs with a donor star of $2 - 6 M_{\odot}$ can avoid a spiral-in stage and evolve into IMBPs by rapid mass transfer on a thermal timescale (Tauris et al. 2000; Podsiadlowski et al. 2002; Pfahl et al. 2003). Based on the isotropic re-emission model, Tauris et al. (2000) found that IMXBs can evolve into IMBPs with relatively long orbital period ($P_{\text{orb}} \approx 3 - 50$ d). Recently, the population-synthesis calculation also shows that it is difficult to form BMSPs with $P_{\text{orb}} < 10$ d by the standard binary star evolution (Hurley et al. 2010).

At present, there exist 9 compact IMBPs with an orbital period of less than 3 d. Therefore, it is very interesting for the stellar evolutionary theory to account for the origin of these compact IMBPs. These systems could be explained if the NS survives a phase of common envelope (CE) evolution with an intermediate-mass donor star. The post-CE system consists of a NS and a He star (the naked core of the donor star). Because He stars with a mass less than $2 M_{\odot}$ can evolve into CO WDs by burning their helium shell (Habets 1986), NS + He star binaries can form most of the observed IMBPs by Case BB mass transfer from naked He stars (Tauris et al. 2012). It is worth noting that NS + He star binaries have an ultra-short orbital periods in the range of $0.01 - 1.0$ d due to common envelope evolution (Chen et al. 2011). Recently, Chen & Liu (2013) have investigated the initial parameter space (He star masses and initial orbital periods) of He star + NS binaries that can form IMBPs. Their simulated results show that the NS + He star evolutionary channel can explain the formation of $4 - 5$ short orbital period IMBPs. The discrepancies between the simulation and the observations may originate from the accretion model of the NS and the magnetic braking scenario, which should be improved.

The aim of this work is to investigate whether the IMXBs evolutionary channel can form compact IMBPs without evolving through a CE-phase. The majority of intermediate-mass stars (more than $1.5 M_{\odot}$) with radiative envelopes are not thought to experience magnetic braking. However, about 5% of A/B type stars possess anomalously strong magnetic fields (about $100 - 10000$ G), and they are called Ap/Bp stars¹ (see also Landstreet 1982; Moss 1989; Shorlin et al. 2002; Braithwaite & Spruit 2004). Justham et al. (2006) found that magnetic braking scenarios of Ap/Bp stars can account for the formation of compact black hole X-ray binaries with short orbital periods of less than 1 d.

Unfortunately, the operation process of magnetic dynamo in the early-type stars with a radiative envelope is still unclear (Dervişoğlu et al. 2010). In this work, solar-like magnetic braking concepts are simply applied to intermediate-mass stars with an anomalous magnetic field. We apply

this anomalous magnetic braking model to the evolution of IMXBs, and test whether IMXBs can provide an alternative evolutionary channel to compact IMBPs. This paper is structured as follows. In section 2, we will give a detailed description for the binary evolution calculation of IMXBs. The calculated results are presented in section 3. Finally, we give a brief summary and discussion in section 4.

2 INPUT PHYSICS

2.1 Stellar evolution code

Based on an updated version of the stellar evolution code originally developed by Eggleton (1971, 1972, 1973; see also Han et al. 1994; Pols et al. 1995), we attempt to simulate the evolutionary sequences of IMXBs consisting of a NS (of mass M_{NS}) and an Ap/Bp donor star (of mass M_{d}). The Ap/Bp donor star is assumed to be a solar chemical composition ($X = 0.70, Y = 0.28, Z = 0.02$), the ratio of the mixing length to the pressure scale height and the convective overshooting parameter are set to be 2.0 and 0 (Dewi et al. 2002). The stellar OPAL opacity table is taken from Chen & Tout (2007), Rogers & Iglesias (1992), and Alexander & Ferguson (1994). We stop the calculation when the system evolves into a detached binary, and the donor star evolves into a WD.

2.2 Mass transfer and angular momentum loss

The mechanisms driving the mass transfer in IMXBs should be the loss of orbital angular momentum via gravitational wave radiation and/or magnetic braking (for narrow systems with initial orbital period of $1 - 2$ d), and the nuclear evolution of the donor star (for relatively wide systems with initial orbital periods of greater than $1 - 2$ d). In our calculation, we considered three kinds of angular momentum loss as follows.

1. Gravitational wave radiation. This angular momentum loss rate is given by (Landau & Lifshitz 1975)

$$\dot{J}_{\text{GR}} = -\frac{32G^{7/2}}{5c^5} \frac{M_{\text{NS}}^2 M_{\text{d}}^2 M^{1/2}}{a^{7/2}}, \quad (1)$$

where G and c are the gravitational constant and the speed of light in vacuum, respectively. $M = M_{\text{NS}} + M_{\text{d}}$ is the total mass of the binary, and a is the binary separation.

2. Mass loss. For IMXBs, once the donor star overflows its Roche lobe, thermal timescale mass transfer is triggered because the material is transferred from the more massive donor star to the less massive NS. The mass transfer rate $-\dot{M}_{\text{d}}$ may be greater than the Eddington accretion rate of the NS, in which $\dot{M}_{\text{Edd}} \simeq 1.5 \times 10^{-8} M_{\odot} \text{yr}^{-1}$ for H-rich accreted material. Therefore, the mass-loss rate of the system can be written as $|\dot{M}| = |\dot{M}_{\text{d}}| - |\dot{M}_{\text{Edd}}|$. For the angular momentum loss accompanying the mass loss, we assume an isotropic re-emission scenario (Soberman et al. 1997), in which the excess material is ejected in the vicinity of the NS, and carries away the specific orbital angular momentum of the NS. The orbital angular momentum loss rate by the isotropic re-emission is given by

$$\dot{J}_{\text{IR}} = \frac{\dot{M}_{\text{d}} M_{\text{d}}^2}{M^2} a^2 \Omega \beta, \quad (2)$$

¹ Ferrario et al. (2009) argued that the upper-main sequence stars with strong magnetic field originated from a merge of two protostars. The strong differential rotation drove by merger process can lead to a large-scale dynamo field.

where Ω is the orbital angular velocity of the binary system, β is the fraction of material lost from the donor star which is re-emitted from the NS (Soberman et al. 1997).

3. Magnetic braking of Ap/Bp stars. The interaction between the magnetic field of a donor star and its stellar winds can extract the spin angular momentum (Weber & Davis 1967; Mestel & Spruit 1987; Kawaler 1988). Similarly to Justham et al. (2006), we assume that the stellar wind is bound in the magnetic field lines to co-rotate with the stars out to the magnetospheric radius (r_m). However, the tidal interaction between two components would accelerate the donor star to co-rotate with the orbital motion, and indirectly remove the orbital angular momentum from the binary. Therefore, the loss rate of angular momentum by magnetic braking is

$$\dot{J}_{\text{MB}} = -\Omega r_m^2 \dot{M}_{\text{wind}} = -(GM_d)^{-1/4} \Omega B_d R_d^{13/4} \dot{M}_{\text{wind}}^{1/2}, \quad (3)$$

where \dot{M}_{wind} is the stellar wind-loss rate; B_d , and R_d denote the surface magnetic field, and the radius of the Ap/Bp star, respectively.

Actually, Ap/Bp stars in main sequence stage are not observed to have spun down because of weak winds. However, in a close binary system X-rays generated by accretion on to the NS can drive a strong stellar wind from the Ap/Bp star (Ruderman et al. 1989a; Tavani & London 1993). Therefore, the anomalous magnetic braking of Ap/Bp star provides an efficient mechanism extracting angular momentum from the X-ray binaries. To obtain the the stellar wind-loss rate, we assume that a fraction of the X-ray luminosity of the NS is converted into the kinetic energy of a wind of the donor star. I. e.

$$\frac{GM_d \dot{M}_{\text{wind}}}{R_d} = L_X f_\Omega f_\epsilon, \quad (4)$$

where f_Ω is the geometric factor of the X-ray flux intercepted by the donor star, and f_ϵ is the wind driving energy efficiency factor (Justham et al. 2006). The X-ray luminosity of the accreting NS can be written as

$$L_X = 0.1 \dot{M}_{\text{acc}} c^2, \quad (5)$$

where \dot{M}_{acc} is the accretion rate of the NS. By equations (3), (4), (5), and Kepler's third law, we obtain (see also equation (15) in Justham et al. 2006)

$$\dot{J}_{\text{MB}} = -B_d \left(\frac{\psi \dot{M}_{\text{acc}} M}{a^3} \right)^{1/2} \left(\frac{R_d^{15}}{GM_d^3} \right)^{1/4}, \quad (6)$$

where $\psi = 0.1 f_\Omega f_\epsilon c^2$ is a synthetic parameter. Since $\dot{J}_{\text{MB}} \propto B_d \psi^{1/2}$, the calculated results are more sensitive to B_d than to ψ . Therefore, we only consider the influence of magnetic field on the calculated results. Similarly to Justham et al. (2006), we take $f_\Omega = 0.01$, $f_\epsilon = 10^{-3}$, so $\psi = 10^{-6} c^2$. The angular momentum loss rate was found to decrease when the donor star becomes completely convective (Rappaport, Verbunt & Joss 1983; Spruit & Ritter 1983). Therefore, in the stellar code we stop the magnetic braking mechanism when the donor star mass is less than $0.3 M_\odot$, at the point where the star enters the fully convective stage.

2.3 Spin and magnetic field evolution of the NS

In the stellar evolution code, we also take into account the evolution of the spin and the surface magnetic field (B_{NS})

of NSs. For the spin evolution, the NS is assumed to experience three evolutionary stages comprising an accretion phase, a propeller phase, and a radio phase (see also section 2.3 of Liu & Chen 2011 and Table 1 of Chen & Liu 2013). In addition, there also exists a spin-down torque originating from the magnetic coupling between the magnetic field of the spinning NS and the outer region of the accretion disc (Ghosh & Lamb 1979; Ruderman et al. 1989b). Considering the accretion torque, the propeller torque, and the spin-down torque caused by the interaction between the magnetic field and the accretion disc, the total torque exerted on the NS can be written as (Dai & Li 2006)

$$N = \begin{cases} -\dot{M}_d \sqrt{GM_{\text{NS}} R_0} \left[\xi(1 - \omega) + \frac{\sqrt{2}}{3} (1 - 2\omega + \frac{2\omega^2}{3}) \right], & (\omega \leq 1) \\ -\dot{M}_d \sqrt{GM_{\text{NS}} R_0} \left[\xi(1 - \omega) + \frac{\sqrt{2}}{3} (\frac{2}{3\omega} - 1) \right], & (\omega > 1) \end{cases} \quad (7)$$

where $N = dJ_{\text{NS}}/dt = Id\Omega_{\text{NS}}/dt$, R_0 is the magnetospheric radius of the NS, ξ is a parameter depending on the structure of the magnetosphere. In calculation, we take a moderate value $\xi = 0.5$, and a constant moment of inertia $I = 10^{45} \text{ g cm}^2$. The fastness parameter $\omega = \Omega_{\text{NS}}/\Omega_0$, where Ω_{NS} is the angular velocity of the NS, Ω_0 is the (Keplerian) angular velocity at the magnetosphere radius.

For the magnetic field evolution, we simply take a phenomenological form of magnetic field decay due to the accretion given by Shibazaki et al. (1989). I. e.

$$B_{\text{NS}} = \frac{B_i}{1 + \Delta M / 10^{-4} M_\odot}, \quad (8)$$

where B_i and ΔM are the initial magnetic field and the accreted mass of the NS, respectively.

In our calculation, we assume that the NS has passed through the death line before it was recycled. Observations show that the critical voltage (generated above the polar cap of the pulsar) line satisfies $B_{\text{NS}}/P_s^2 \approx 2 \times 10^{11}$ (P_s is the pulse period, Rawley et al. 1986), and a theoretical study also presented a similar estimate by Ruderman & Sutherland (1975). In addition, the pulse periods of known radio pulsars are in the range of 1.4 ms – 11 s (Manchester 2004). The final spin period of the NS during the recycled process is insensitive to its initial spin period and magnetic field (Wang et al. 2011). Therefore, we take an initial spin period of 10 s, a typical magnetic field of 10^{12} G , and a canonical initial NS mass of $1.4 M_\odot$.

3 SIMULATED RESULTS

Fig. 1 summarizes our simulated results by showing the evolutionary fate of IMXBs in the initial Ap/Bp star masses vs. the initial orbital periods diagram. It is seen that, if the initial orbital period in the range of 2 – 4 d, IMXBs with a relatively low-mass ($2.0 - 2.8 M_\odot$) Ap/Bp stars can evolve into LMBPs with a He WD. While for relatively high-mass Ap/Bp stars with a mass of $2.6 - 3.8 M_\odot$, IMXBs can form IMBPs with a CO WD if the initial orbital period is in the range of 2 – 6 d, depending on the donor star mass. If the donor star is in a close binary (P_{orb} less than 1 d), during

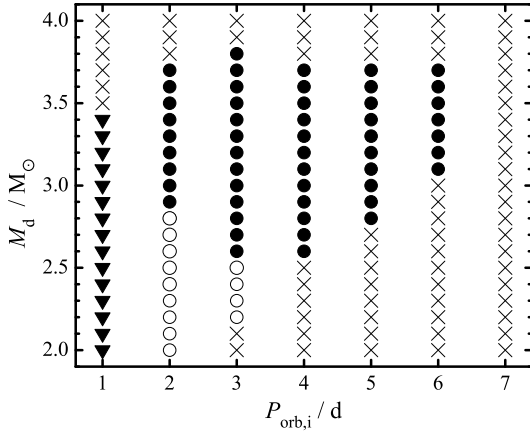


Figure 1. Distribution of the initial Ap/Bp star masses $M_{d,i}$ and the initial orbital periods $P_{orb,i}$ of IMXBs that can evolve into binary pulsars by the anomalous magnetic braking of Ap/Bp stars when $B_d = 1000$ G. The filled circles and open circles represent the IMBPs, and LMBPs, respectively. The crosses correspond to IMXBs that experience dynamically unstable mass transfer and common envelope evolution. The filled triangles denote systems where the mass transfer persists after a Hubble time.

the Roche-lobe overflow the orbital separation continuously decreases because the material is transferred from the more massive donor star on to the less massive NS. The shrinking Roche-lobe causes the donor star to overfill its Roche-lobe even more, unstable mass transfer commences and the system experiences common envelope evolution (Tauris et al. 2000). Similarly, if the initial orbital period is more than 7 d, long timescale nuclear evolution of the donor star before the mass transfer causes the formation of a deep convective envelope. Subsequently, a runaway material transfer is triggered, giving rise to the spiral-in of the NS and common envelope evolution. The anomalous magnetic braking mechanism is very efficient in removing angular momentum from binaries. Employing the magnetic braking, IMXBs with a short orbital period ($\lesssim 1$ d) evolve into relatively compact X-ray binaries until the donor star mass is less than $0.3 M_\odot$. Subsequently, gravitational radiation causes the continuous shrinking of the Roche lobe, and triggers a new mass-transfer episode. Therefore, in these systems the mass transfer persists after a Hubble time (see the filled triangles in Fig. 1). Finally, the donor star can not evolve into WD, but remains with a semi-degenerate He core. It is worth noting that, considering anomalous magnetic braking in our work, the initial parameter space that can form binary pulsars is smaller than found in previous works (Tauris et al. 2000; Shao & Li 2012).

In order to illustrate the influence of the magnetic field on the orbital period of IMBPs, in Fig. 2 we present the correlation between the final orbital period $P_{orb,f}$ and the surface magnetic field B_d of Ap/Bp stars with different masses when the initial orbital period of IMXBs $P_{orb,i} = 2.0$ d. For the same donor star, the simulated results of four different magnetic field including 0, 200, 1000, and 3000 G are shown. The filled squares, the open circles and the open squares correspond to the initial Ap/Bp star with mass $2.5 M_\odot$, $3.0 M_\odot$ and $3.5 M_\odot$, respectively. As shown in this figure, when B_d

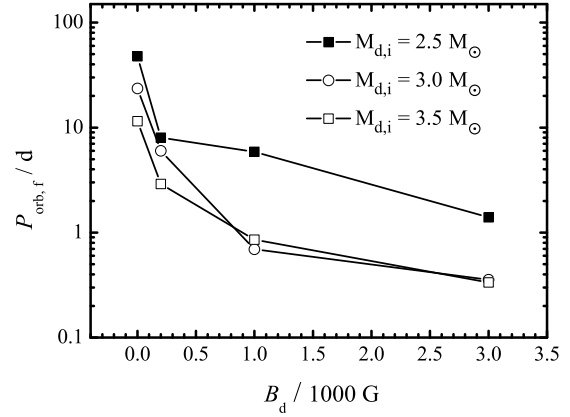


Figure 2. The final orbital periods $P_{orb,f}$ of IMBPs as a function of the surface magnetic fields B_d of Ap/Bp stars when the initial orbital period of IMXBs $P_{orb,i} = 2.0$ day. The solid squares, open circles, and open squares correspond to the donor star masses of 2.5, 3.0, and $3.5 M_\odot$, respectively.

$= 0$ IMXBs evolve into IMBPs with a relatively long orbital period (10 – 50 d). However, relatively weak magnetic braking of Ap/Bp stars ($B_d = 200$ G) can result in a moderately long orbital period (3 – 8 d). And strong anomalous magnetic braking of Ap/Bp stars ($B_d = 1000$, or 3000 G) can induce the birth of compact IMBPs with an orbital period of 0.2 – 1 d when the donor star mass $M_d \geq 3 M_\odot$.

In Fig. 3, we plot the evolutionary track of the mass transfer rate and the orbital period of the NS IMXB with a donor star of $3.0 M_\odot$ and an initial orbital period of $P_{orb,i} = 2.0$ d under different magnetic fields, $B_d = 200$ and 3000 G. Fig. 4 shows the evolution of the NS mass and the donor star mass when the donor star has magnetic field $B_d = 200$, 3000 G. With the exhaustion of central H, the donor star starts to fill its Roche-lobe at the age of 322.1 Myr. Because the material transfer from the more massive donor star to the less massive NS, the first stage is the thermal timescale mass transfer and lasts about 1 Myr. The rapid mass transfer occurs at a high rate of about $10^{-6} M_\odot \text{yr}^{-1}$ until the donor star mass decreases to $1.4 M_\odot$. In the first stage, the NS only accretes about $0.01 M_\odot$ ($1.5 \times 10^{-8} M_\odot \text{yr}^{-1} \times 1$ Myr), and 99.4% of the transferred material is ejected by the radiation pressure of the NS. In the second stage, the nuclear burning of remaining H in the core drove the mass transfer at a rate of $10^{-8} - 10^{-7} M_\odot \text{yr}^{-1}$. The NS accreted $0.06 - 0.08 M_\odot$ in a time-interval of 4 – 6 Myr. This is consistent with the conclusion of Podsiadlowski et al. (2002), that IMXBs spent more than 80% of their X-ray active lifetime as LMXBs. Though the NS only accretes less than $0.1 M_\odot$ of the transferred material, it can be sufficiently spun up to 3.57 ms ($B_d = 200$ G) or 5.51 ms ($B_d = 3000$ G) (see Fig. 5). If the donor star has a weak surface magnetic field of 200 G, the orbital period continuously increases to 5.5 d, then decreases to 4.5 d, and then increases again to 6.0 d. However, IMXBs including Ap/Bp stars with a strong magnetic fields (3000 G) can evolve into a compact IMBPs with an orbital periods of around 0.35 d. Therefore, it seems that strong magnetic braking of Ap/Bp stars could possibly play an important

Table 1. Measured parameters of 18 known IMBPs.

PSR	P_s (ms)	P_{orb} (days)	References
long orbital period	IMBPs	$(P_{\text{orb}} \gtrsim 3 \text{ d})$	
J1420–5625	40.3	34.1	1
J1810–2005	32.8	15.01	2
J1904+0412	71.1	14.93	2
J1454–5846	45.2	12.42	2
J1614–2230	3.15	8.69	3,4
J0621+1002	28.9	8.319	5,6
J1022+1001	16.5	7.805	6
J2145–0750	16.1	6.839	7
J1603–7202	14.8	6.309	8
short orbital period	IMBPs	$(P_{\text{orb}} \lesssim 3 \text{ d})$	
J1157–5112	43.6	3.507	9
J1528–3146	60.8	3.18	10
J1439–5501	28.6	2.12	11,12
J1232–6501	88.3	1.86	2,13
J1435–6100	9.35	1.35	2,13
B0655+64	195.7	1.03	14,15
J1802–2124	12.6	0.699	11,16
J1757–5322	8.87	0.453	17
J1952+2630	20.7	0.392	18

References. (1)Hobbs et al. (2004); (2)Camilo et al. (2001); (3)Crawford et al. (2006); (4)Demorest et al. (2010); (5)Splaver et al. (2002); (6)Camilo et al. (1996); (7)Bailes et al. (1994); (8)Lorimer et al. (1996); (9)Edwards & Bailes (2001a); (10)Jacoby et al. (2007); (11)Faulkner et al. (2004); (12)Lorimer et al. (2006); (13)Manchester et al. (2001); (14)Jones & Lyne (1988); (15)Lorimer et al. (1995); (16)Ferdman et al. (2010); (17)Edwards & Bailes (2001b); (18)Knispel et al. (2011).

role in forming IMBPs with a short orbital period, as an alternative to post-CE evolution.

Fig. 6 shows the distribution of our simulated results in the final orbital period vs. the final spin period plane of IMBPs when the magnetic field of Ap/Bp stars $B_d = 1000$ G. As shown in this figure anomalous magnetic braking of Ap/Bp stars can evolve IMXBs into compact IMBPs with a short orbital period (less than 10 d) and a small spin period (less than 20 ms). The minimum of the orbital period of IMBPs forming by this evolutionary channel is about 0.6 d. In Table 1, we compile the observed orbital period and spin period for 18 IMBPs. To test our evolutionary model, 18 IMBPs by the stars are also shown in Fig. 6. One can see that our simulated results can only account for the formation of a few IMBPs. The far majority of the observed compact IMBPs tend to have long spin-periods. This discrepancy may originate from our accretion model, in which we assume the accretion rate of the NS $\dot{M}_{\text{NS}} = \min[\dot{M}_{\text{Edd}}, |\dot{M}_d|]$. Actually, $\dot{M}_{\text{NS}} = f \times \min[\dot{M}_{\text{Edd}}, |\dot{M}_d|]$, and $f < 1$ (see also Tauris et al. 2013; Lazarus et al. 2014). In Fig.5, we show the influence of the parameter f on the final spin period of the NS. One can see that, a moderate parameter $f = 0.5$ can result in a twice increase of the spin period.

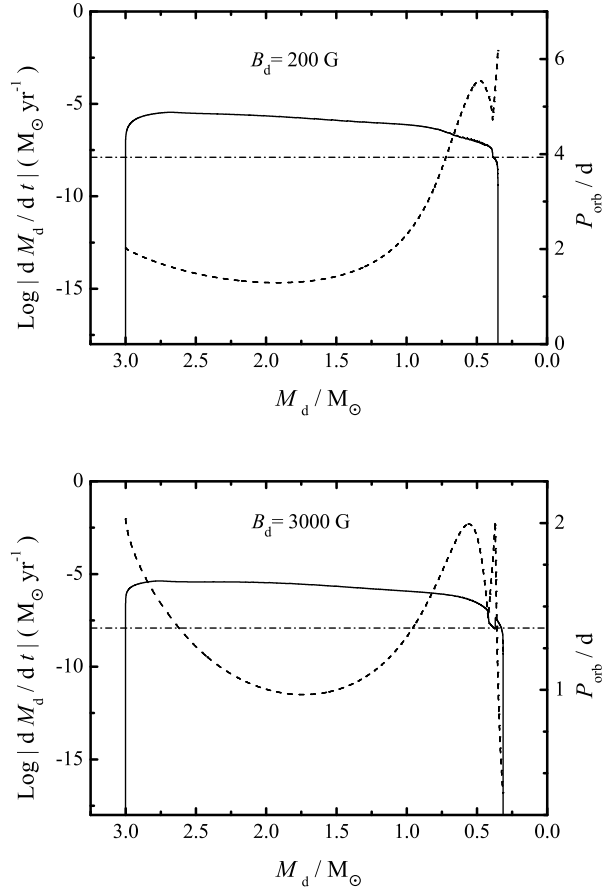


Figure 3. Evolutionary tracks of a NS IMXB with an Ap/Bp star of $3.0 M_\odot$ and an initial orbital period of $P_{\text{orb},i} = 2.0$ d. In the upper panel, and lower panel, the donor star has a surface magnetic field of 200, and 3000 G, respectively. The solid and dashed curves represent the evolution of the mass transfer rate and the orbital period, respectively. The horizontal line corresponds to the Eddington accretion rate.

4 DISCUSSION AND SUMMARY

In this paper, we aim at a peculiar binary pulsar problem, namely the evolutionary origin of compact IMBPs with an orbital period of less than 3 d. Considering an anomalous magnetic braking model of Ap/Bp stars proposed by Justham et al. (2006), we have performed evolutionary calculations of NS + Ap/Bp star binaries consisting a $1.4 M_\odot$ NS and a $2.0 - 4.0 M_\odot$ Ap/Bp star companion, and have tested whether this evolutionary channel can produce compact IMBPs. Our main results and conclusions are summarized as follows.

1. Assuming the surface magnetic fields of Ap/Bp stars are 1000 G, IMXBs with a $2.6 - 3.8 M_\odot$ donor star and an orbital period of $2.0 - 6.0$ d can evolve into IMBPs. Beyond this initial parameter space, most IMXBs would undergo common-envelope evolution due to the unstable mass transfer process.

2. About 90% of our simulated IMBPs have an orbital period less than 3 d. Therefore, we propose that IMXBs including Ap/Bp stars with a relatively strong magnetic field

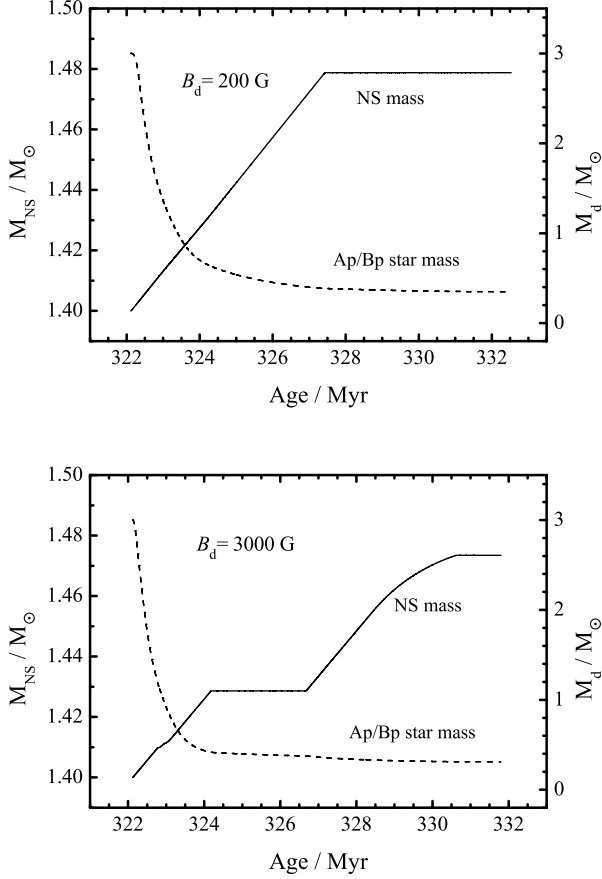


Figure 4. Evolutionary tracks of a NS IMXB with an Ap/Bp star of $3.0 M_{\odot}$ and an initial orbital period of $P_{\text{orb},i} = 2.0$ d. In the upper panel, and lower panel, the donor star has a surface magnetic field of 200, and 3000 G, respectively. The solid and dashed curves represent the evolution of the NS mass and the Ap/Bp star mass, respectively.

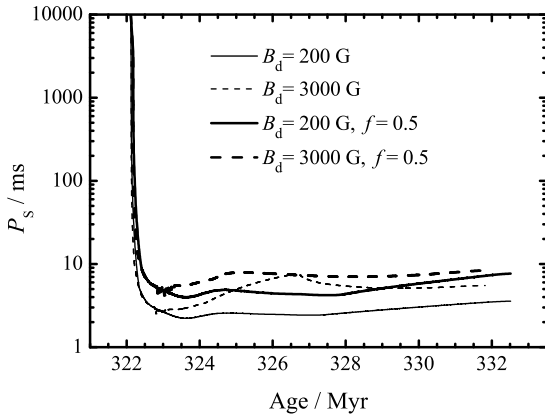


Figure 5. Evolution of spin period of the NS in an IMXB with an Ap/Bp star of $3.0 M_{\odot}$ and an initial orbital period of $P_{\text{orb},i} = 2.0$ d. The solid and dashed curves correspond the system in which the donor star has a surface magnetic field of 200, and 3000 G, respectively.

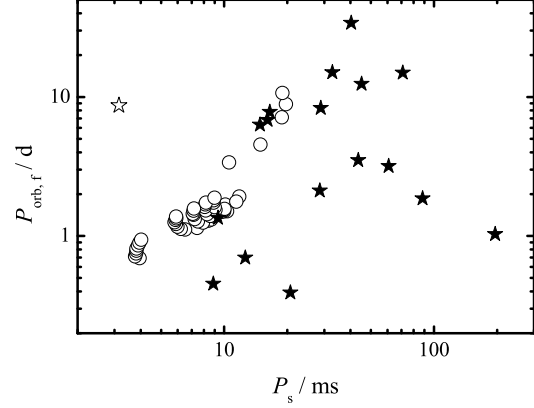


Figure 6. Comparison between our simulated results (open circles) and the observed data (solid stars) in the final orbital period vs. the final spin period of IMBPs diagram when the magnetic field of Ap/Bp stars $B_d = 1000$ G. Note: The open star represents PSR J1624-2230, which is so far the only known IMBP formed via Case A Roche-lobe overflow.

are potential progenitors of compact IMBPs, especially in case a NS cannot survive the spiral-in during a CE.

3. The efficiency of magnetic braking plays a vital role for the orbital period of IMBPs. If Ap/Bp stars have a weak magnetic field of 200 G, such an evolutionary channel leads to the formation of IMBPs with a relatively long orbital period of 3 – 8 d. However, for a strong magnetic field of more than 1000 G, compact IMBPs with an orbital period of less than 1 d can be formed.

4. When $B_d = 1000$ G, anomalous magnetic braking scenario only gives rise to the formation of IMBPs with a short spin-period of less than 20 ms, which is obviously lower than the observed period of most IMBPs. There may be two cases to address this discrepancy. In the first case, the NS accretion model in our calculation should be improved. In the second case, there exist other evolutionary channels to form IMBPs with a relatively long spin-period (see also Tauris et al. 2012; Chen & Liu 2013; Lazarus et al. 2014). It is very interesting that anomalous magnetic braking scenarios can form IMBPs with an orbital period of more than 0.6 d and a spin period of less than 10 ms, which cannot be produced by the NS + He star evolutionary channel (see also Fig. 4 of Chen & Liu 2013).

Certainly, there exist many uncertainties in our calculation. First, for initial input parameters we adopt a canonical NS mass of $1.4 M_{\odot}$. However, both theoretical studies (see also Nomoto 1984) and observations (e. g. Kiziltan et al. 2010; Zhang et al. 2011) argue that the initial masses of NSs have a large range distribution. Recently, two groups suggested that the peculiar IMBP PSR J1614-2230 could have evolved from an IMXB with a heavy NS (about $1.6 - 1.7 M_{\odot}$, Lin et al. 2011; Tauris et al. 2011). Subsequently, Shao & Li (2012) found that the initial parameter space (in the initial orbital period vs. the initial donor star mass diagram) forming binary pulsars expands when the NS mass increases. Secondly, we simply take a constant magnetic field strength ($B_d = 1000$ G). Actually, Ap/Bp stars may have a large distribution range of 100 – 10000 G in the surface magnetic field

(Moss 1989; Braithwaite & Spruit 2004). This would significantly influence the evolutionary fate of IMXBs. Thirdly, for the X-ray irradiation-driven stellar wind process by the mass accretion, in this calculation we take a constant synthetic parameter ψ like Justham et al. (2006). However, this parameter may change from one system to another. Fourthly, the prescription for magnetic braking is highly uncertain. Fifthly, the magnetic field decay equation of the NS due to accretion needs to be improved.

A potential caveat of the work presented here is if the tidal forces can keep the spin of the donor star synchronized with the orbital motion. Magnetic braking of a star extracting orbital angular momentum is based on the significant tidal interaction between the orbit and the star. Studying the spin evolution of the accreting Algol-type binaries, Dervişoğlu et al. (2010) found tidal interaction between the components and the orbit is too weak to efficiently remove spin angular momentum from the accreting component. The weak energy dissipation for stars with radiative envelopes should be responsible for this weak tide. Therefore, magnetic braking of Ap/Bp stars need an efficient energy dissipation mechanism that is stronger than gravity wave dissipation (Zahn 2005). In addition, at the end of the mass-transfer phase the donor star has a relatively thin envelope. It is unclear if the tidal forces are still efficient for a thin envelope. This issue goes beyond the scope of this work, and we plan to explore it in a subsequent work.

ACKNOWLEDGMENTS

We are grateful to the anonymous referee for helpful comments. This work was partly supported by the National Science Foundation of China (under grant number 11173018, U1331117), Innovation Scientists and Technicians Troop Construction Projects of Henan Province, China.

REFERENCES

Alexander D. R., Ferguson J. W., 1994, *ApJ*, 437, 879
 Alpar M. A., Cheng A. F., Ruderman M. A. Shaham J., 1982, *Nature*, 300, 728
 Bailes M. et al., 1994, *ApJ*, 425, L41
 Bhattacharya D., van den Heuvel E. P. J., 1991, *Phys. Rep.*, 203, 1
 Braithwaite J., Spruit H. C., 2004, *Nature*, 431, 819
 Brown G. E., 1995, *ApJ*, 440, 270
 Brown G. E., Lee C.-H., Portegies Zwart S. F., Bethe H. A., 2001, *ApJ*, 547, 345
 Camilo F., Nice D. J., Shrauner J. A., Taylor J. H., 1996, *ApJ*, 469, 819
 Camilo F. et al., 2001, *ApJ*, 548, L187
 Chen W.-C., Li X.-D., Xu R.-X., 2011, *A&A*, 530, A104
 Chen W.-C., Liu W.-M., 2013, *MNRAS*, 432, L75
 Chen X., Tout C. A., 2007, *Chin. J. Astron. Astrophys.*, 7, 245
 Chevalier R. A., 1993, *ApJ*, 411, L33
 Crawford F., Roberts M. S. E., Hessels J. W. T., Ransom S. M., Livingstone M., Tam C. R., Kaspi V. M., 2006, *ApJ*, 652, 1499
 Dai H.-L., Li X.-D., 2006, *A&A*, 451, 581

Demorest P. B., Pennucci T., Ransom S. M., Roberts M. S. E., Hessels J. W. T., 2010, *Nature*, 467, 1081
 Dervişoğlu A., Tout C. A., Ibanoglu C., 2010, *MNRAS*, 406, 1071
 Dewi J. D. M., Pols O. R., Savonije G. J., van den Heuvel E. P. J., 2002, *MNRAS*, 331, 1027
 Edwards R. T., Bailes M., 2001a, *ApJ*, 547, L37
 Edwards R. T., Bailes M., 2001b, *ApJ*, 553, 801
 Eggleton P. P., 1971, *MNRAS*, 151, 351
 Eggleton P. P., 1972, *MNRAS*, 156, 361
 Eggleton P. P., 1973, *MNRAS*, 163, 279
 Faulkner A. J. et al., 2004, *MNRAS*, 355, 147
 Ferdman R. D. et al., 2010, *ApJ*, 711, 764
 Ferrario L., Pringle J. E., Tout C. A., Wickramasinghe D. T., 2009, *MNRAS*, 400, L71
 Ghosh P., Lamb F. K., 1979, *ApJ*, 234, 296
 Habets G. M. H. J., 1986, *A&A*, 187, 209
 Han Z., Podsiadlowski P., Eggleton P. P., 1994, *MNRAS*, 270, 121
 Hobbs G. et al., 2004, *MNRAS*, 352, 1439
 Hurley J. R., Tout C. A., Wickramasinghe D. T., Ferrario L., Kiel P. D., 2010, *MNRAS*, 402, 1437
 Iben I., Jr., Livio M., 1993, *PASP*, 105, 1373
 Jacoby B. A., Bailes M., Ord S. M., Knight H. S. Hotan A. W., 2007, *ApJ*, 656, 408
 Jones A. W., Lyne A. G., 1988, *MNRAS*, 232, 473
 Justham S., Rappaport S., Podsiadlowski Ph., 2006, *MNRAS*, 366, 1415
 Kawaler S. D., 1988, *ApJ*, 333, 236
 Kiziltan B., Kottas A., Thorsett S. E., 2010, *arXiv:1011.4291*
 Knispel B. et al., 2011, *ApJ*, 732, L1
 Konar S., Bhattacharya D., 1997, *MNRAS*, 284, 311
 Landau L. D., Lifshitz E. M., 1975, *The Classical Theory of Fields* (Oxford: Pergamon Press)
 Landstreet J. D., 1982, *ApJ*, 258, 639
 Lazarus P. et al., 2014, *MNRAS*, 437, 1485
 Li X.-D., 2002, *ApJ*, 564, 930
 Lin J., Rappaport S., Podsiadlowski Ph., Nelson L., Paxton B., Todorov P., 2011, *ApJ*, 732, 70
 Liu W.-M., Chen W.-C., 2011, *MNRAS*, 416, 2285
 Lorimer D. R., Yates J. A., Lyne A. G., Gould D. M., 1995, *MNRAS*, 273, 411
 Lorimer D. R., Lyne A. G., Bailes M., Manchester R. N., D’Amico N., Stappers B. W., Johnston S., Camilo F., 1996, *MNRAS*, 283, 1383
 Lorimer D. R. et al., 2006, *MNRAS*, 372, 777
 Lorimer D. R., 2008, *Living Rev. Relativ.*, 11, 8
 Manchester R. N. et al., 2001, *MNRAS*, 328, 17
 Manchester R. N., 2004, *Science*, 304, 542
 Mestel L., Spruit H. C., 1987, *MNRAS*, 226, 57
 Moss D., 1989, *MNRAS*, 236, 629
 Nomoto K., 1984, *ApJ*, 277, 791
 Paczynski B., 1976, in *IAU Symp. 73, Structure and Evolution in Close Binary Systems*, ed. P. P. Eggleton, S. Mitton, & J. Whealan (Dordrecht: Reidel), 75
 Pfahl E., Rappaport S., Podsiadlowski P., 2003, *ApJ*, 597, 1036
 Podsiadlowski P., Rappaport S., Pfahl E. D., 2002, *ApJ*, 565, 1107
 Pols O. R., Tout C. A., Eggleton P. P., Han Z., 1995, *MNRAS*, 274, 964

- Radhakrishnan V., Srinivasan G., 1982, *Current Science*, 51, 1096
- Rappaport S., Verbunt F., Joss P. C., 1983, *ApJ*, 275, 713
- Rawley L. A., Taylor J. H., Davis M. M., 1986, *Nature*, 319, 383
- Rogers F. J., Iglesias C. A., 1992, *ApJS*, 79, 507
- Ruderman M., Sutherland P. G., 1975, *ApJ*, 196, 51
- Ruderman M., Shaham J., Tavani M., Eichler D., 1989a, *ApJ*, 343, 292
- Ruderman M., Shaham J., Tavani M., 1989b, *ApJ*, 336, 507
- Shao Y., Li X.-D., 2012, *ApJ*, 756, 85
- Shibazaki N., Murakami T., Shaham J., Nomoto K., 1989, *Nature*, 342, 656
- Shorlin S. L. S., Wade G. A., Donati J.-F., Landstreet J. D., Petit P., Sigut T. A. A., Strasser S., 2002, *A&A*, 392, 637
- Soberman G. E., Phinney E. S., van den Heuvel E. P. J., 1997, *A&A*, 327, 620
- Splaver E. M., Nice D. J., Arzoumanian Z., Camilo F., Lyne A. G., Stairs I. H., 2002, *ApJ*, 581, 509
- Spruit H. C., Ritter H., 1983, *A&A*, 124, 267
- Stairs I. H., 2004, *Science*, 304, 547
- Tauris T. M., Savonije G. J., 1999, *A&A*, 350, 928
- Tauris T., van den Heuvel E. P. J., Savonije G. J., 2000, *ApJ*, 530, L93
- Tauris T. M., van den Heuvel E. P. J., 2006, in *Formation and Evolution of Compact Stellar X-ray Sources*, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 623
- Tauris T. M., Langer N., Kramer M., 2011, *MNRAS*, 416, 2130
- Tauris T. M., Langer N., Kramer M., 2012, *MNRAS*, 425, 1601
- Tauris T. M., Sanyal D., Yoon S.-C., Langer N., 2013, *A&A*, 558, A39
- Tavani M., London R. A., 1993, *ApJ*, 410, 281
- van den Heuvel E. P. J., Taam R. E., 1984, *Nature*, 309, 235
- van den Heuvel E. P. J., 1994, *A&A*, 291, L39
- Verbunt F., Zwaan C., 1981, *A&A*, 100, L7
- Wang J., Zhang C. M., Zhao Y. H., Kojima Y., Yin H. X., Song L. M., 2011, *A&A*, 526, A88
- Webbink R. F., 1984, *ApJ*, 277, 355
- Weber E. J., Davis L., 1967, *ApJ*, 148, 217
- Zahn J.-P., 2005, in Claret A., Giménez A., Zahn J.-P., eds, *ASP Conf. Ser. Vol. 333, Tidal Evolution and Oscillation in Binary Stars: Third Granada Workshop on Stellar Structure*. Astron. Soc. Pac., San Francisco, p. 4
- Zhang C. M. et al., 2011, *A&A*, 527, A83

This paper has been typeset from a $\mathrm{T}_{\mathrm{E}}\mathrm{X}/\mathrm{L}^{\mathrm{A}}\mathrm{T}_{\mathrm{E}}\mathrm{X}$ file prepared by the author.